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The Effect on Vision of Light Scatter from HMD Visors and Aircraft Windscreens

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ABSTRACT

The amount of scattered light, or haze, typically increases as transparent materials age, wear, become dirty, or become scratched from cleaning. Light scattered from scratched aircraft transparencies, such as windscreens, head-up-display combiners, and helmet visors, can potentially reduce pilot visual performance and reduce target detection range. Presented in this paper are the results of an investigation of light scattered from transparencies exhibiting different levels of wear and surface damage. Two methods of measuring scattered light are compared. Visual performance under conditions of white light scatter relevant to the use of helmet-mounted displays in the cockpit is also examined.

Keywords: light scatter, haze, vision, contrast threshold, visor

1. INTRODUCTION

Helmet-mounted display (HMD) visors, just like other military aircraft visors, are made of plastic and are subject to scratching as they are worn, handled, and cleaned. The scratches can be relatively large and easily visible [Maier, 1996] or they could be micro-scratches that are not easily visible unless the lighting is just right. In either case the scratches and micro-scratches can scatter light causing a reduction in contrast of objects viewed through the visor. This light scattering from a transparency is commonly referred to as haze. Maximum allowable amounts of haze for visors are called out in military specifications for new visors [Mil Spec MIL-V-85374(AS), 1979]. Haze is usually measured using ASTM (American Society for Testing and Materials) Standard Test Method D-1003 [ASTM D1003] which is based on an older Federal Test Method 3022 under Federal Standard 406 (see Figure 1). In this Test Method, haze is defined as the ratio of the scattered light to the total light that gets through a transparency and is usually expressed as a percent. ASTM D-1003 provides an easy and highly repeatable procedure for assessing the amount of light scattered from a transparency and is well suited for laboratory work or acceptance testing procedures. However, it does have some drawbacks. It is supposed to be limited to thin, flat, unscratched parts but for the windscreen assessment application it is used on thick, curved, and (sometimes) scratched parts. While this test provides a convenient single index (percent haze) to characterized the light scatter of a material, it does not provide any indication of the distribution of the light scatter. Without knowing the distribution of the light scatter it is impossible to predict the visual effects that could be expected. This paper presents a methodology for measuring the light scatter distribution from several transparencies (mostly sections of aircraft windscreens but the procedure applies to any transparent material) and discusses an approach to modeling the light scatter to predict the resulting contrast loss and effect on visual performance.

2. METHOD

Two methods of measuring light scatter from transparent materials were employed in this study. The first of these methods, documented in ASTM D-1003, employed a beam of white light and an integrating sphere to measure haze, a single valued assessment of scatter. The second method involved making measurements of light scattered from a sample with respect to the angle at which the light scattered, in spherical coordinates. This method, documented in ASTM E-167, produces detailed information on the angular distribution of the scatter.

2.1 ASTM D 1003 Equipment and Procedure

Probably the most common test method for measuring haze in transparent parts is ASTM D-1003. This ASTM Standard Test Method defines haze as the percent of the transmitted light that is scattered. This test calls for passing a collimated beam of white light through a sample and an integrating sphere, as depicted in Figure 1. The unscattered beam is allowed to pass through the sphere (and therefore is not measured by the photo-detector) and out a hole at the opposite side while the scattered light is collected and measured. The port in the rear of the sphere is then closed and the total light transmitted through the sample is measured. The ratio of the scattered light to the total transmitted light, including the scattered component, is then reported as the sample's haze, or an integrated value for scatter.

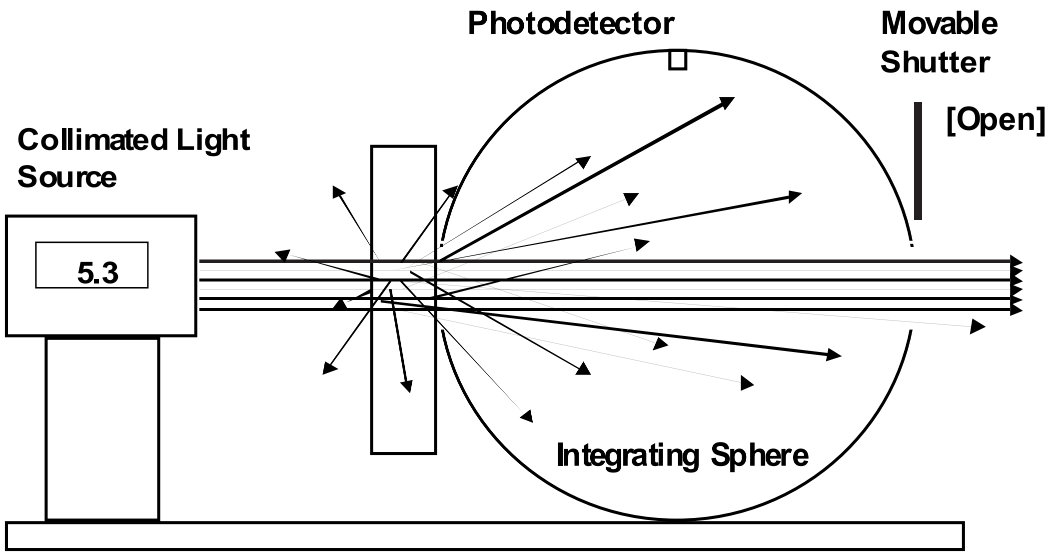

Figure 1. Diagram of ASTM D-1003.

The instrument used to conduct these measurements was a Hazeguard System model XL-211 produced by Pacific Scientific. Because some of the samples were scratched more on one side than the other and were fairly thick (up to 0.9 inch) each sample was measured two ways: with side A toward the integrating sphere and with side B toward the sphere. The Hazeguard System measures to the nearest tenth of a percent haze. The haze values obtained in the Results section are the average of 10 measurements taken from each side then averaged and recorded to the nearest hundredth of a percent.

2.2 Bi-directional Transmission Distribution Measurement Equipment and Procedure

An extremely sensitive technique that has the ability to capture the angular behavior of scatter is the bi-directional transmission distribution function (BTDF) measurement, described in many forms [Bartell, 1980] [Nicodemus, 1977] including ASTM E-167. This involves illuminating a transparent sample and measuring the light scattered from the sample as a function of two angles, often expressed in polar coordinates. The light source used in these experiments to illuminate an approximately 24 mm diameter circular area on the sample was a 35 Watt quartz-halogen bulb, diffused using Opal glass, and focused into the sample near its rear surface, creating the highest intensity in the scattering surface under examination. Stability of this source's luminance output was monitored by an independent photometer. Scattered light measurement was accomplished using a small photometer with a 0.25 inch square collecting surface, subtending 1 degree in both horizontal and vertical dimensions as seen from the sample, that was rotated on an arm about an axis passing through the sample's rear surface. Data collected and recorded by computer included readings from both photometers, the measurement number, the time of the measurement, and the angular position of the scatter measuring photometer. Photometer measurements were an average of 10 readings at each data point. The sample was then rotated 90 degrees about an axis through the sample's center, perpendicular to its surface and the measurement repeated. Data gathered in this fashion yields a somewhat incomplete set. However, the missing information can be generated mathematically by curve fitting, assuming a certain level of symmetry and orthogonality. The assumption of symmetry must be applied carefully since it is not always applicable, such as in measurements where the incident light is not normal to the surface in at least one axis.

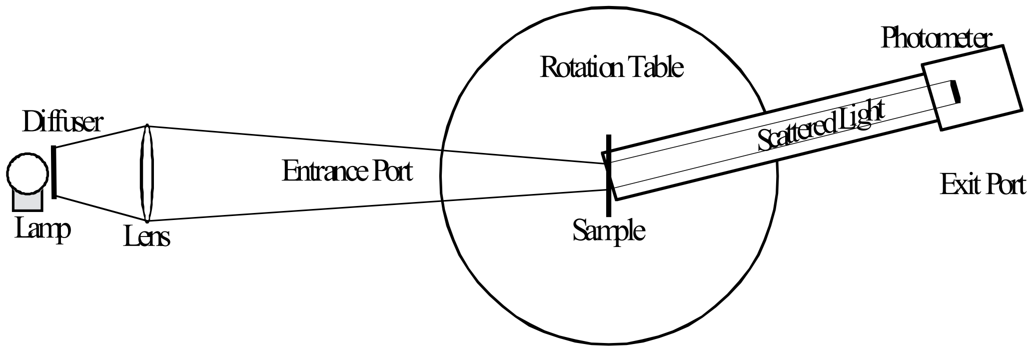

Figure 2. BTDF measurement diagram

Scatter is heavily dependent on the surface quality and cleanliness of a sample. As a result, simple precautions were taken when handling and storing the samples between measurements to prevent the addition of dirt to the surfaces, which could potentially corrupt the data. In particular, the samples were stored in a clean environment, in a cleanroom hood, between measurements. Also, samples were dusted with high-pressure air before each measurement.

2.3 Samples Measured

The scatter from ten transparent samples of different materials, thicknesses, number of layers, coatings, ages, and degrees of wear was measured in these experiments. Table 1 is a listing of the samples with some descriptive information regarding their physical characteristics.

Table 1. Description of samples measured.

#	Sample	Thickness (in)	Layers	Surface Quality	Coating
1	F-16	0.638	3	New	Gold
2	F-15	0.897	1	New	None
3	Acrylic	0.887	1	Scratched	None
4	F-111	0.775	9	Unused	None
5	Plexiglas	0.138	1	Scratched	None
6	F-16	0.731	3	Scratched	Gold
7	F-111	0.769	5	Scratched	None
8	F-111	0.711	5	Scratched	None
9	Haze Std. 5%	0.155	1	Rough	None
10	Haze Std. 10%	0.155	1	Rough	None

3. RESULTS

The results of the optical scatter measurements conducted using both methods appear in Table 2. Most of the samples exhibited modest levels of haze. A few samples exhibited haze values that would change with respect to the surface measured. Often this was due to surface structure. One surface was simply rougher than the other. However, In one case, the scatter was primary from an interface between two layers.

Table 2. Measured and calculated haze for ten samples.

#	Sample	Haze - A (%)	Haze - B (%)	Int Haze (%)
1	F-16 New	0.49	0.52	0.91
2	F-15 New	0.74	0.74	0.77
3	Acrylic Scratched	0.78	0.81	0.80
4	F-111 Flat Unused	1.07	1.09	1.14
5	Plexiglas Scratched	1.21	1.23	1.54
6	F-16 Scratched	1.80	1.71	1.90
7	F-111 Flat	3.06	3.06	3.26
8	F-111 Scratched	3.22	3.14	3.23
9	Haze Std. 5%	3.75	3.73	3.20
10	Haze Std. 10%	10.24	10.30	8.87

More interesting results were obtained when the BTDF measurements were plotted with respect to measurement angle, or observation angle. Some of these results appear in Figures 3, 4, and 5. It should be noted that the data in these figures are normalized to the maximum luminous flux passing through the sample. These results are not true BTDF values and are intended to illustrate trends is light scatter with respect to measurement angle.

In Figure 3, the angular dependence of scattered light is plotted for a sample having 10.3% haze (black line) and 0.5% haze (gray line), showing the extremes of the samples measured. This implies that lower haze samples can scatter significantly at small observation angles. However, their scattering drops much more quickly as observation angle increases than the higher haze sample. This would not be of great interest if this were true in all cases. However, measurements showed that in some cases and at some angles, a lower haze sample could scatter more light than one of higher haze.

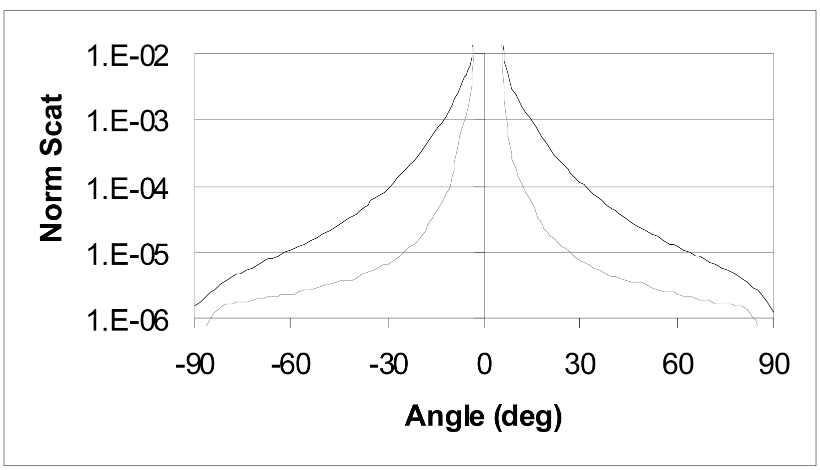

Figure 3. Angular dependence of scatter from normally incident light.

Figure 4 shows the angular nature of scatter for a 1.80% haze sample (sample #6, gray line) and one measured at 3.22% haze (sample #8, black line). One can see that for large observation angles, greater than 45 degrees, the lower haze sample will scatter more strongly. This can be quite significant since, in some cases, an observer's line of sight can pass through a scattering transparency at large angles when measured with respect to the surface normal. Haze measurements will not accurately predict visual performance under these circumstances.

Figure 5 shows a plot of normalized scattered light with respect to observation angle for non-normally incident illumination on the 10.3% haze sample. For this measurement, the angle of incidence was approximately 26 degrees. The plot is noticeably asymmetric, shifted about the angle of incident illumination. This illustrates another phenomenon that ASTM D-

1003 haze measurements can not quantify completely. To successfully execute the D-1003 standard, measurements should be taken with the sample perpendicular to the incident beam. Modifying the procedure to make such measurements is possible. However, the procedure would no longer be firmly based on an ASTM standard. Measurement equipment would also require modification to accommodate samples of different thicknesses and wedge angles. Difference like these would require changes in the integrating sphere's entrance and exit port to optimize the technique. This constant modification may become tedious when measuring a large number of physically different samples.

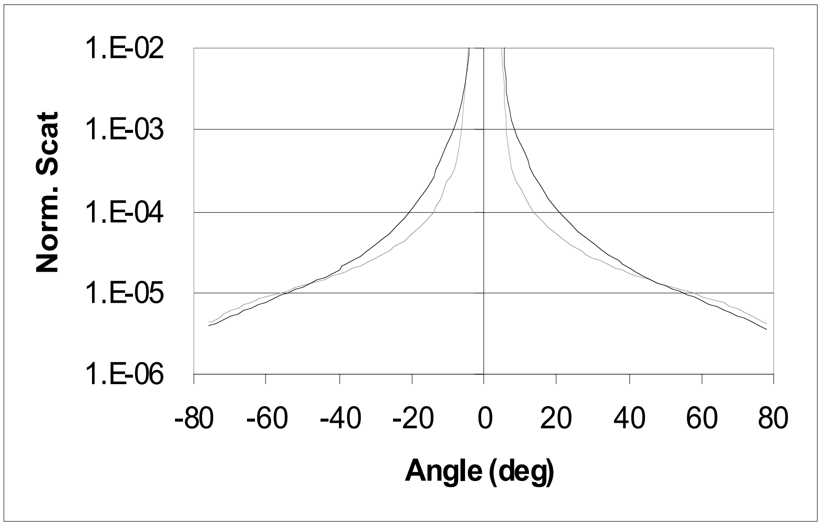

Figure 4. Angular dependence of scatter from normally incident light.

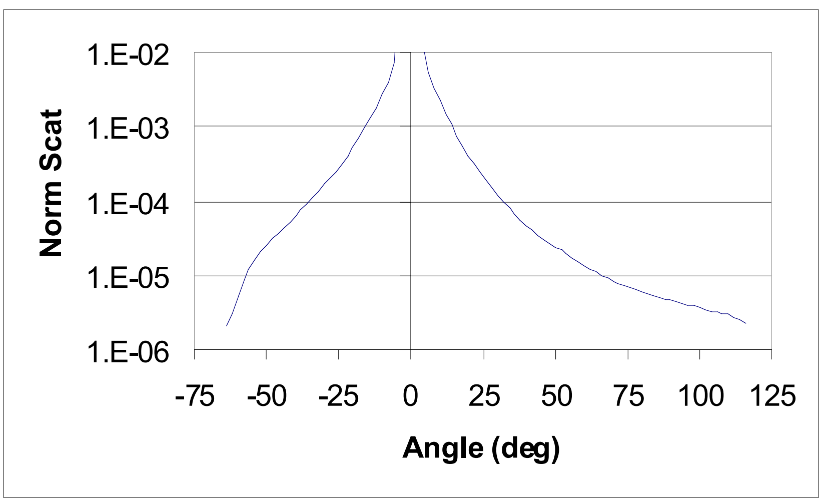

Figure 5. Angular dependence of scatter from non-normally incident light (incidence angle of 26 degrees).

A comparison was made to determine agreement between the angular measurements and haze measurements made using ASTM D-1003. To make this comparison, a value for haze was calculated from the BTDF measurements for each sample. To accomplish this, the BTDF measurements were integrated assuming radial symmetry. Total energy transmitted through each sample was calculated by measuring the total energy incident on the sample and multiplying by the sample transmissivity. The integrated haze values were then divided by the calculated total energy transmitted and appear in Table 2. Figure 6 shows the relationship between integrated haze and ASTM D-1003 measurements plotted against a line having a unity slope. Statistical analysis indicated a non-unity slope (slope of 0.83) and a non-zero intercept (intercept of 0.36) with an R^2 correlation of 0.993. Perfect agreement between the two methods would have yielded a statistical linear model having a slope of unity and an intercept at the origin.

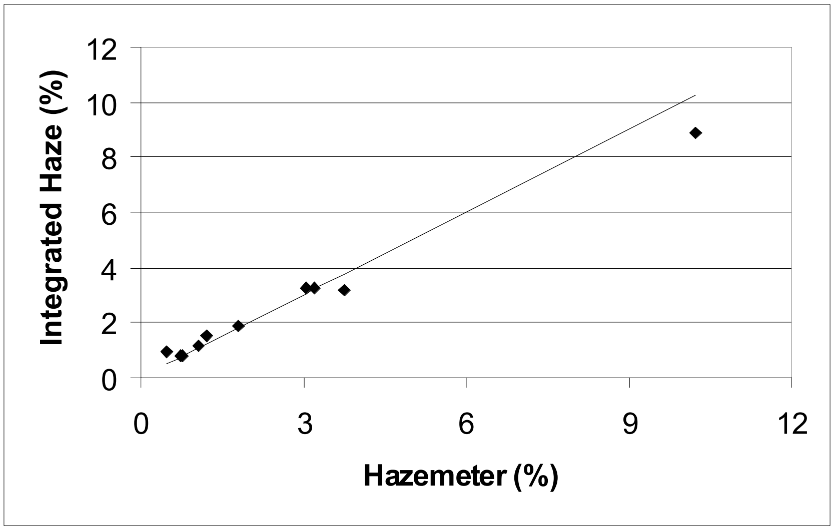

Figure 6. Integrated haze values versus Hazemeter (ASTM D-1003).

4. DISCUSSION

4.1 Range of haze and haze distributions

It is apparent from the results shown in Figure 3 that the scattering distributions for the different samples are different. In other words, it is not possible to take a generic scatter distribution and simple multiply by a constant to get the scatter distribution from another sample. The shape of the distribution is dependent on the sample and what within (or on) the sample is causing the scatter. It should also be noted that, according to the results shown in Figure 5, the scattering distributions are not symmetric when the sample is tilted at an angle to the incident light source.

4.2 Utility of haze measurement methods

As noted earlier, there are some limitations to ASTM D-1003. It is only recommended for flat, thin, transparent parts that scatter light from only one surface. Realistically, transparencies of interest tend to be thick, curved materials that scatter form both surfaces and from the bulk material itself [Task & Genco, 1985]. ASTM D-1003 cannot assess scatter from non-normal incidence beams and, most significantly, it yields no information on the angular distribution of the scattered light. This makes the ASTM D-1003 method unsuitable for developing a model to predict the impact of haze on visual performance. A good example of this is shown in Figure 4, which is a plot of the results obtained for samples number 6 and 8. Even though sample 8 had a higher measured haze value (3.22% using ASTM D-1003) than sample 6, it is apparent from the graph of Figure 4 that scattering is greater for sample 6 once the viewing angle is past about 45 degrees since the scatter distributions cross over at approximately this angle. If observers were required to view targets through these samples in the proper geometry, they would see that the lower haze value sample caused a higher degree of target contrast loss than the higher haze value sample (as measured by ASTM D-1003).

BTDF measurements suffer from their own set of drawbacks. First, the tests are time consuming even when automated and therefore are not very well suited to acceptance testing. They easily require much more time to complete than measurements made using ASTM D-1003. BTDF measurements yield no single metric by which one can easily describe a transparent part. Also, the level of detail produced by BTDF measurements may be inappropriate or even excessive for some applications. However, this method does provide a full description of the scattered light angular distribution making it well suited for visual effects modeling.

4.3 Effect of scattered light on target detection and vision

Developing details regarding modeling the effects of light scatter on visual performance is considered beyond the scope of this paper. However, we will present the basic approach to developing such models. There are several equations that are used to define contrast, all of which calculate some value that relates to two luminance levels: typically the "target" and the "background." The equation used to calculate contrast is irrelevant, the end result of light scatter (veiling luminance) will be the same: a reduction in the value of the contrast. Figure 7 shows this effect.

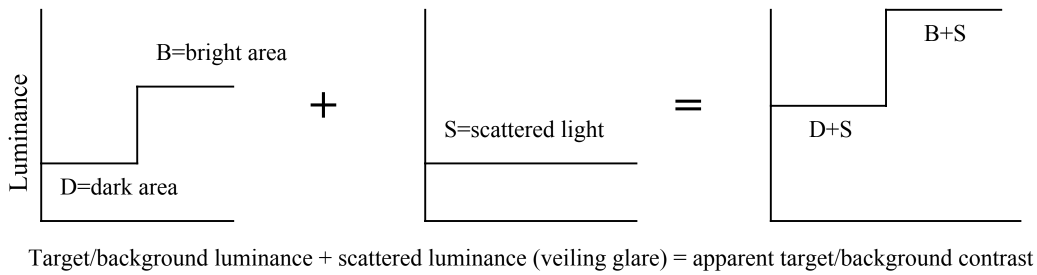

Figure 7. Effect of scattered light (haze or veiling luminance) on target to background contrast.

To illustrate this affect let's look at the modulation (or Michelson) equation for contrast:

$$C = \frac{B - D}{B + D} \tag{1}$$

Where: B= the bright portion (either target or background)
D= the dark portion (either background or target)
C= target/background contrast.

If a veiling luminance were added to both the target and the background the observed contrast would now be:

$$C_o = \frac{(B+S)-(D+S)}{(B+S)+(D+S)} = \frac{B-D}{B+D+2S} \tag{2}$$

Where: S= the apparent luminance caused by the scattered light.
C_o = the observed contrast

Since B, D, and S are all positive values, the apparent contrast is reduced by the addition of scattered light when compared to the directly viewed target/background contrast. To demonstrate that the result is essentially the same regardless of the definition of contrast that is used, this can be repeated using the expression for differential contrast:

$$C_d = \frac{B - D}{D} \tag{3}$$

After the scattered luminance is added to both the bright and dark parts of the scene the observed differential contrast is:

$$C_{do} = \frac{(B+S)-(D+S)}{(D+S)} = \frac{B-D}{D+S} \tag{4}$$

Since all values are positive, and since the denominator of the fraction has been increased by “S,” it is once again apparent that the observed differential contrast is lower than the scene without the veiling luminance.

No matter what equation you use for contrast it is possible to take the veiling luminance values obtained from the light scatter distributions and determine the effect on the contrast of any target/background combination. The next step is to use any convenient model of human visual target detection or recognition based on contrast effects to predict the effect of the veiling luminance, or scatter, on visual performance. These can be the visual models based on sine waves [Campbell & Robson, 1968], or those based on circular disks [Blackwell, 1946], or any other vision model approach.

5. CONCLUSION

The angular distribution of scattered light is important to consider when trying to understand the effect of optical scatter on vision. It is possible for a low haze sample (as measured by ASTM D-1003) to scatter more at high observation angles than a sample measured to have a higher haze value. At some angles of observation, a low haze sample can actually scatter more light towards an observer than one with a higher haze. The two approaches to measuring optical scatter examined here were ASTM D-1003 and measurement of BTDF. Both techniques have strengths and weaknesses that must be considered when assessing a transparent material's inherent scatter. Statistical agreement between the two is good but not perfect. Levels of haze, which are seen as acceptable, can have a significant effect on observer visual performance. The angular dependence of scatter will change the impact of scatter depending on geometry and observer task. A number of other factors, such as interocular scatter, visual noise, accommodative trapping, and visual masking, are at work simultaneously with scatter, making their effects difficult to extract.

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BIOGRAPHIES

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Peter Marasco came to the U.S. Air Force in 1991 as a research physicist. His work as an optical engineer has been primarily in the areas of Night Vision and Aircraft Transparency Technology conducting basic research, guiding and executing optical and opto-mechanical design efforts, evaluating concepts and prototypes, and developing and improving optical test methods. Mr. Marasco received a BS degree from the University of Rochester in 1991 and an MS degree from the University of Arizona in 1993, both in Optical Engineering. Currently, he is working toward a Ph.D. from the University of Dayton in Electro-Optical Engineering. He is a member of the SAFE Association and the Society of Photo-Optical Instrumentation Engineers (SPIE).

H. Lee Task has been employed as a research scientist for the US Air Force since 1971. He has served as chief scientist for the Armstrong Aerospace Medical Research Laboratory (prior to its reorganization and disestablishment in 1991) and in March of 1997 was selected as the Senior Scientist for Human-Systems Interface of the new Air Force Research Laboratory at Wright-Patterson AFB, Ohio. He is currently involved in research and development in the areas of helmet-mounted displays, vision through night vision goggles, optical characteristics of aircraft windscreens, vision, and display systems. He has a BS Degree in Physics (Ohio University), MS degrees in Solid State Physics (Purdue, 1971), Optical Sciences (University of Arizona, 1978), and Management of Technology (MIT, 1985) and a PhD in Optical Sciences from the University of Arizona Optical Sciences Center (1978). During his career he has earned 40 patents and has published more than 80 journal articles, proceedings papers, technical reports, and other technical publications. He is a member of the Human Factors and Ergonomics Society (HFES), the American Society for Testing and Materials (where he is chairman of Subcommittee F7.08 on Aerospace Transparencies and is a Fellow of the Society), the Association of Aviation Psychologists, SAFE association where he is the editor of the SAFE Journal, the Society for Information Display (SID), and SPIE (the optical engineering society).